Final Report

NNSO6AA78G, "Improving water resources management in the western U.S. through use of remote sensing data and seasonal climate forecasts"

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This was a joint project of the University of Washington and the University of California, Irvine (PI S. Sorooshian). It was aimed at utilizing NASA remote sensing data and hydrologic and climate prediction models in a partnership with three operational water management agencies – the Natural Resources Conservation Service, which provides seasonal streamflow forecasts over most of the west, the U.S. Bureau of Reclamation, which has decision authority within the Klamath River basin (where there have been ongoing and highly publicized conflicts over water allocation), and the California Department of Water Resources, which has decision authority for much of the Sacramento River basin. The project leverages heavily from the University of Washington's west-wide hydrologic forecast system (http://www.hydro.washington.edu/forecast/westwide). While the primary focus of this research was on water management, there are secondary benefits for the energy sector, particularly hydropower. This report covers work conducted the University of Washington, and by U.C. Irvine (under contract to UW)

The project consisted of seven tasks as follows:

Task 1: Klamath River forecast system enhancements

"The existing UW west-wide forecast system will be enhanced for application in the Klamath R. basin. In particular, we will add forecasts points of interest to USBR, and will apply MODIS SCA updating that we have previously tested in the Snake River basin. We will modify the current UW forecast system to a 1/16 degree grid resolution (currently 1/8 degree), to capture smaller drainage areas within the Upper Klamath River area. We will migrate the forecast system so that it can be run at NWCC, with performance monitored by both the UW team as well as USBR Klamath Basin Area Office operational staff."

We implemented and calibrated a streamflow forecasting system at UW with a 1/8 degree resolution for the western United States and a 1/16 degree resolution for the Klamath River basin (Figure 1). In November 2006, UW held discussions with Klamath Falls USBR water managers, who indicated an intention to de-emphasize the use of seasonal forecasts and migrate toward an operational management approach that placed higher weight on nowcasts of moisture conditions (snowpack, soil moisture and river flow). The new UW system (http://www.hydro.washington.edu/forecast/rsda/) thus contains daily nowcast capabilities for soil moisture and snowpack conditions that support more frequent forecast updates than were possible with the original West-wide system. In *addition, MODIS snow cover, MODIS snow fraction, and MODIS snow albedo from the 500 m resolution MOD10A1 data sets are assimilated within the model via the direct insertion method. The benefit from updating was found to be greatest during the snow melt season, when streamflow is most essential for irrigated agriculture, demonstrating the potential MODIS products have for regional water management.*

A number of analyses were performed in support of system implementation. SNOTEL and California Cooperative Snow Surveys observations were compared with snow data derived from five satellite/model sources; the best agreement was found with MODIS SCA 8-day composite data, blended SSM/I SWE data, and VIC model output, particularly at elevations above 1500 m and during the winter months. We performed comparisons of SWE data observed by SNOTEL with VIC-simulated SWE data, both with and without MODIS SCA data assimilation, and observed streamflows with those simulated by VIC, again with and without MODIS SCA data assimilation. In addition, the availability of MODIS SCA data was compared with the availability of ground snow data for 799 stations in the western United States. Due to cloud cover, MODIS SCA data was found to have the greatest availability (~70%) in summer and the lowest (~40%) in winter, while the availability of ground snow data was generally about 90%.

Publications resulting from this task:

Tang Q, Lettenmaier DP (2009) Use of satellite snow-cover data for streamflow prediction in the Feather River basin, California. International Journal of Remote Sensing (accepted).

Conference presentations resulting from this task:

Tang Q, Wood AW, Lettenmaier DP (2008) Near real-time snow data assimilation for streamflow forecasting using MODIS snow data products. AMS 88th Annual Meeting, New Orleans, LA

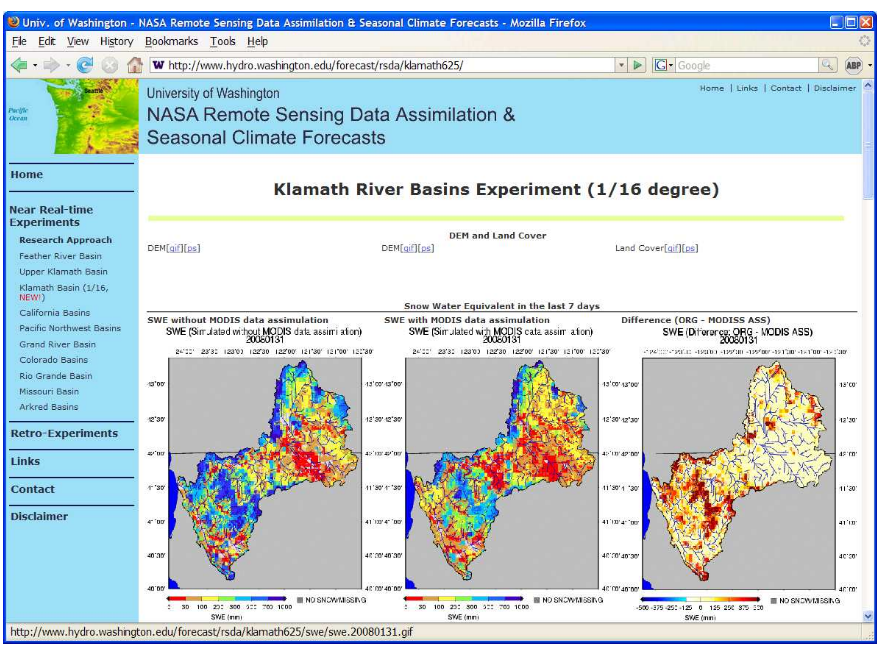

Figure 1: A screenshot of the 1/16 degree Klamath River basin forecasting system, showing nowcasts on January 31, 2008 of VIC-simulated SWE (left), VIC-simulated, MODIS-updated SWE (middle), and the difference between the two (right).

Task 2: Upper Klamath Lake net inflow calculation via remote sensing.

"We will interact with USBR and NWCC to develop post-processed forecasts from our west-wide system that will represent Upper Klamath Lake net inflow (i.e., impairment to reflect the effects of crop water use, reservoir evaporation and ungaged local runoff). The primary alternatives to be explored include: a) a statistical temperature index method, and b) satellite-derived estimates of crop water use and of lake surface temperature, coupled with a VIC-based lake simulation. The two satellite products will be assimilated into the VIC nowcasts during the spin-up period to each forecast date. The results will be evaluated indirectly via comparison with derived UKL net inflows."

For Task 2, UW developed a near real-time ET estimation system over the Sacramento and Klamath River basins (http://www.hydro.washington.edu/forecast/rset_ca/). The system employs a VI-Ts diagram method based on MODIS and NOAA/NESDIS SRB products to map energy partitioning, eliminating the need for surface meteorology data. It runs at a daily time step and 250 m spatial resolution, with a typical time lag of 3 days to 1 week. To support system implementation, retrospective MODIS-derived evapotranspiration estimates were compared with evaporation simulated by the 1/16 degree VIC model and both instantaneous and daily ET observations from tower flux sites in the Klamath River basin (observed by Richard H. Cuenca of Oregon State University).

A pilot application of the ET estimation system was carried out in an assessment of irrigation impacts on Upper Klamath Lake. A combination of remote sensing and hydrologic modeling techniques were used to calculate net irrigation consumption for areas within the Klamath Reclamation Project (Figure 2a), which were then used in conjunction with reservoir inflow data to assess variations in lake water depths (Figure 2b). The water balance simulations illustrated the importance of irrigation withdrawals to lake storage volumes, particularly during the high irrigation season of May to September. In addition to the Sacramento/Klamath domain, a daily-updated Washington Agricultural Monitoring (WAAM) system was implemented (http://www.hydro.washington.edu/forecast/rset_wa/). The objective of WAAM is to monitor hydrologic conditions and to locate and track natural disasters that impair agriculture, such as short and long term droughts, floods, and persistent snow cover. The ET monitoring system of WAAM updates daily at a 250 m spatial resolution. An extension of WAAM to the continental United States has also been implemented at a 0.05 degree spatial resolution (see http://www.hydro.washington.edu/forecast/rset_usa/)

Publications resulting from this task:

Tang Q, Rosenberg EA, Lettenmaier DP (2009) Use of satellite data to assess the impacts of irrigation withdrawals on Upper Klamath Lake, Oregon. Hydrology and Earth System Sciences, 13:617-627.

Tang Q, Peterson S, Cuenca R, Hagimoto Y, Lettenmaier DP (2009) Satellite-based near-real-time estimation of irrigated crop water consumption. Journal of Geophysical Research, 11: D05114,

Tang Q, Gao H, Yeh P, Oki T, Su F, Lettenmaier DP (2009) Dynamics of terrestrial water storage change from satellite and surface observations and modeling. Journal of Hydrometeorology (in press)

Conference presentations resulting from this task:

Tang Q, Wood AW, Lettenmaier DP (2007) Near Real Time Evapotranspiration Estimation Using Remote Sensing Data. AGU Fall Meeting, San Francisco, CA

Tang Q, Peterson S, Cuenca R, Hagimoto Y, Lettenmaier DP (2008) Using remote sensing data to estimate real-time crop water consumption. AGU Fall Meeting, San Francisco, CA

Tang Q Lettenmaier DP (2009) Evapotranspiration Estimates Based on MODIS and Downscaled ISCCP Data. AGU Fall Meeting, San Francisco, CA

Tang Q, Lettenmaier DP (2009) Agricultural monitoring using satellite-based measurements. Fourth global vegetation workshop, Missoula, MT, USA

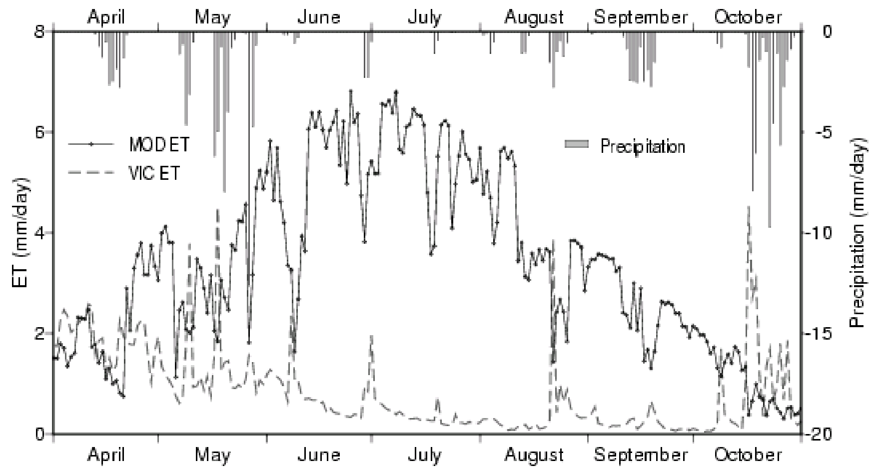

Figure 2a: Daily ET in the Klamath Project's irrigation area during the crop growth season of 2004. Net irrigation consumption is computed as the difference between VIC-simulated ET under natural conditions (dashed line) and MODIS-derived actual ET (solid line).

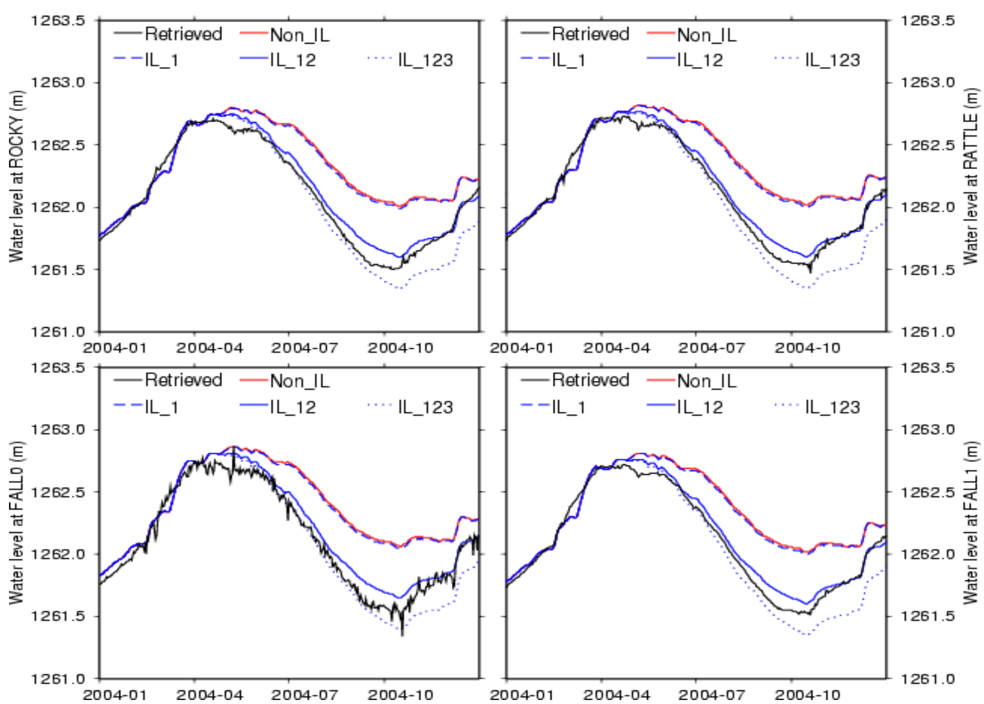

Figure 2b: Simulated and observed water levels at four Upper Klamath Lake USGS stations in 2004. Black line is observed; red line assumes no irrigation; dashed, solid, and dotted blue lines assume irrigation in sequentially increasing areas in the project region.

Task 3: Forecast system implementation/monitoring for Feather/Sac River basins

"Implementation of the UW west-wide forecast system for the Sacramento basin will begin with the Feather R. before expanding to other basins in the Sacramento basin. UCI/UW team members will implement additional forecast points used by DWR, and increase the forecast system spatial resolution (i.e., to a finer grid scale) if necessary. During the first two seasons of the project, the forecasts will run in real-time (parallel to DWR operations) at UCI. Subsequently, modifications in the system required for transition to the DWR environment will be made, and data assimilation algorithms similar to those planned for the Klamath (Task 1) will be implemented."

The major accomplishment for Task 3 was development of the CaliForecast system at UCI. Prior to system implementation, discussions were held with DWR on its current seasonal forecasts, which are issued monthly from February to May and are based on statistical methods using a 50-year climatology. Since the forecasts do not incorporate climate trends (e.g., observed warming in the recent past) or climate variability (e.g., related to ENSO and PDO), potential improvements were offered by a dynamical, physically-based approach. Adapted from UW's West-wide system, the final CaliForecast system included a re-design of internal system architecture, assimilation of both MODIS snow cover data and ground SWE observations through direct insertion, a 1/8 degree forecasting model for the state of California, and a 1/16 degree forecasting model for the Feather River basin. Before system implementation, calibration was achieved from 1904 to 2005 through both a deterministic approach, the Shuffled Complex Evolution algorithm, and a Bayesian particle filtering scheme, one of whose advantages is the ability to provide uncertainty bounds of model parameters, which also facilitates characterization of forecast uncertainty.

In support of system implementation, a number of analyses were performed, including a retrospective evaluation of ESP forecasts for the Feather R basin that provided baseline skill information for subsequent forecasts. Also conducted was an investigation of the snow cover areal depletion curve (i.e., SWE-SCA relationship), which discerned rapidly diminishing values of MODIS SCA when observed SWE was still large, indicative of the thick snow that persists in higher elevations towards the end of the snow melt season, and in contrast to the larger values of SCA simulated by VIC. Finally, we performed direct comparisons of observations with SWE and streamflow data simulated by VIC, both with and without MODIS SCA data assimilation. Again, the VIC model was found to substantially overestimate SCA during the snow ablation period, which, in turn, caused an overestimation of SWE and runoff. The greatest improvement provided by MODIS was thus realized during this time period, when updating had the effect of moderating this result (Figure 3a and 3b).

Conference presentations resulting from this task:

Park GH, Imam B, Ferrer-Capdevila M, Sorooshian S (2007) ESP forecasts for water resources: Model Uncertainty, Climate Uncertainty, or Both? AGU Fall Meeting, San Francisco, CA

Park GH, Imam B, Sorooshian S (2008) Verification and error sources of the California Seasonal Hydrologic Forecast (CaliForecast) System over the Feather River basin. AGU Fall Meeting, San Francisco, CA

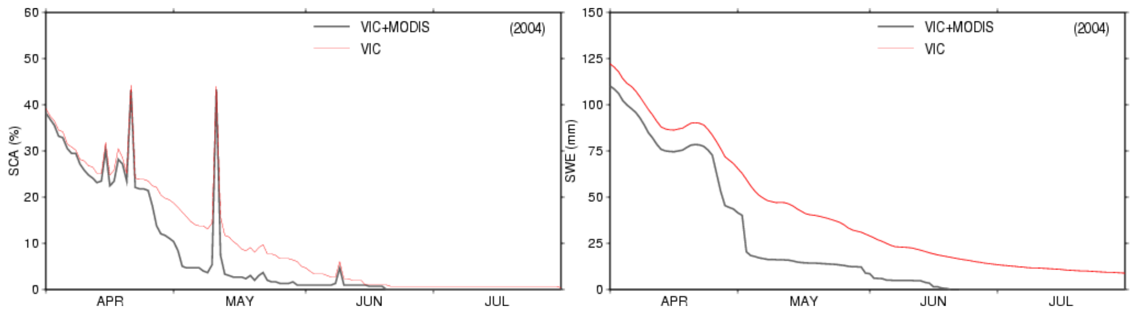

Figure 3a: Basin-averaged SCA (left) and SWE (right), with and without MODIS SCA updating, in the Feather River basin from April to July 2004.

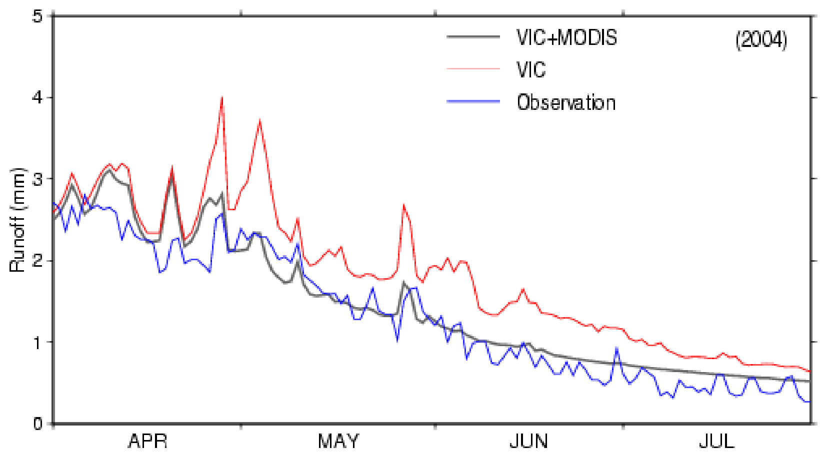

Figure 3b: Observed and VIC-simulated daily runoff, with and without MODIS SCA updating, in the Feather River basin from April to July 2004.

Task 4: Forecast impairment in CADWR/SWP basins

"This task is similar to Task 2. UCI will establish, in consultation with DWR, an arrangement by which forecasted streamflows will be routed through the same decision process currently used by DWR for its operational forecasts. Either DWR will route the forecasts in parallel with their operational ones, or UCI will obtain the necessary algorithms to do so at UCI. UCI will also develop analogous methods applying to forecast system products that are new to DWR."

As part of Task 4, UCI worked closely with the Modeling Support Branch at DWR to implement and calibrate CALSIM-II, the operational reservoir model used to compute forecast impairments by the agency. UCI also performed a retrospective study to provide ESP inputs to DWR at 16 of its forecasting points and provided technical assistance to DWR with the VIC model. Subsequent visits to DWR by UCI focused on means to assist the agency in the area of remote sensing, particularly from NASA data. The two teams identified target areas for improvement and submitted a proposal to NASA to address these issues as a continuation of the efforts in this study

Task 5: Forecast communication (Klamath and Sacramento basins)

"To facilitate NWCC, USBR, and DWR review of forecast system performance, UW/UCI project team members will prepare summary or explanatory reports for (a) regular, real-time forecast updates, and (b) any upgrades or major changes to the experimental forecasting system, and will host conference calls to interpret the results during the course of the forecast season (probably weekly during the period March 1 – June 1, and less frequently at other times). These conference calls and associated reports will be made available via the web. In addition, during the off-season, UW and UCI will host one-day workshops at USBR's Klamath Falls office, and DWR's Sacramento office, to evaluate forecast system performance, and the means by which forecasts were used in the decision process in the previous season."

For Task 5, both UW and UCI maintained close communication with the agencies throughout the study. In January 2007, UW visited DWR's Sacramento headquarters to formally introduce the project and solicit input from DWR personnel. The ensuing development of forecast products was focused by their comments, which expressed a particular interest in the MODIS snow cover area product as a check against field data, and in the MODIS ET product for estimating return flow from irrigated agricultural fields. Further contact with DWR's Division of Flood Management and Operations Control Office helped in gaining a better understanding of DWR's decision-making process in order to find clear examples of benefits that could be derived through improved forecasts.

Two ongoing studies are specifically tailored to integrate hydrologic models and remote sensing data within DWR's operational framework. In the first, VIC-modeled snow water equivalent, snow covered area (SCA), and precipitation are being adapted to DWR's regression-based forecasting system in a hybrid approach that combines physically-based hydrologic simulations with statistically-based equations (Figure 4). The second study involves the direct inclusion of MODIS SCA data as an additional predictor in DWR's statistical framework. In order to extend the MODIS record and lengthen the satellite-based climatology of SCA, UW has obtained daily AVHRR data at a 1/20 degree resolution from NASA's Land Long Term Data Record (http://ltdr.nascom.nasa.gov), which dates to 1981 and is believed to be the longest and highest-resolution AVHRR data set currently in existence. Plans are to extract SCA data from the AVHRR data using a snow cover algorithm described by Zhao and Fernandes (2009). When complete, the satellite climate data record will provide a 28-year climatology for use in regression-based forecasts. Two journal papers are expected to result, which will form part of a graduate student's dissertation.

Conference presentations resulting from this task:

Rosenberg E, Wood AW, Tang Q, Steinemann A, Imam B, Sorooshian S, Lettenmaier DP (2007) Improving water resources management in the western US through use of remote sensing data and seasonal climate forecasts, NOAA CPASW Conference, Seattle, WA

Rosenberg E, Tang Q, Wood AW, Steinemann AC, Lettenmaier DP (2008) Statistical Applications of Physical Hydrologic Models and Satellite Snow Cover Observations to Seasonal Water Supply Forecasts. AGU Fall Meeting, San Francisco, CA

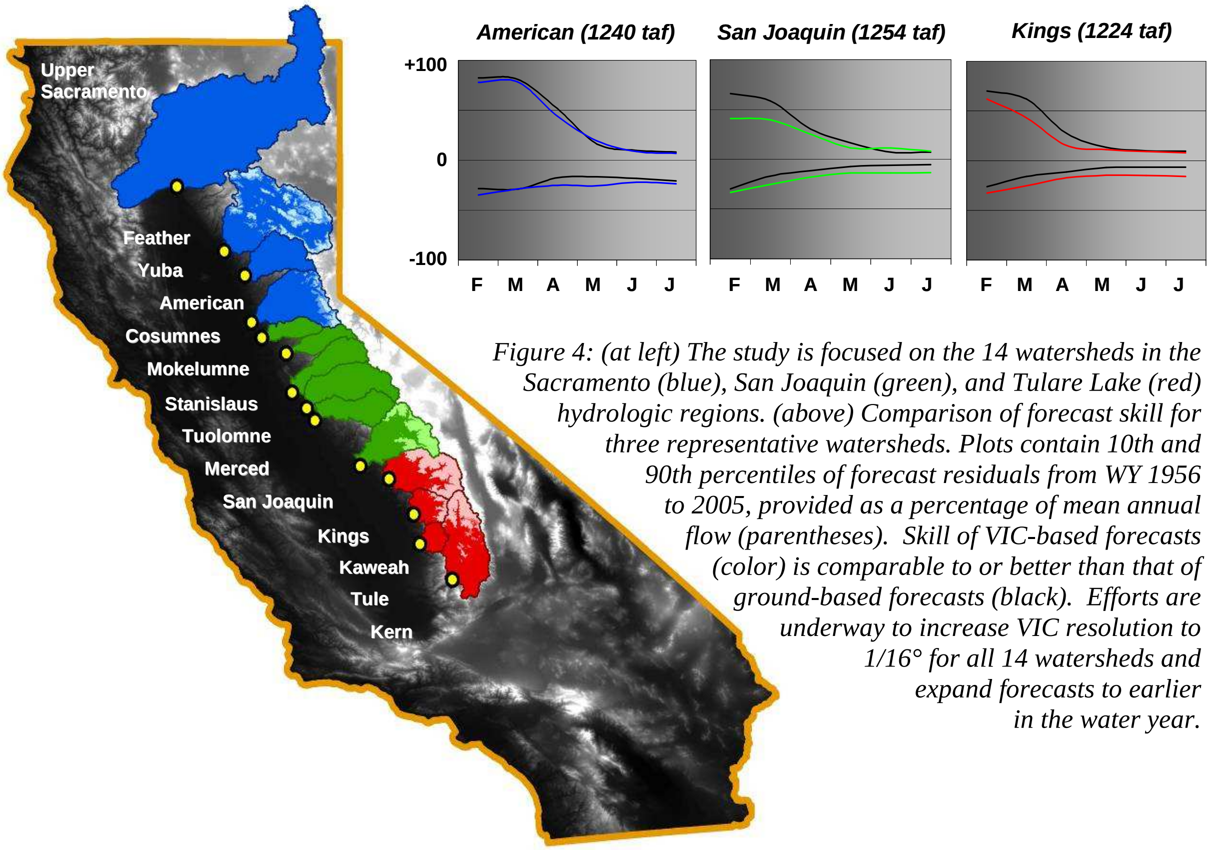

Figure 4: (at left) The study is focused on the 14 watersheds in the Sacramento (blue), San Joaquin (green), and Tulare Lake (red) hydrologic regions. (above) Comparison of forecast skill for three representative watersheds. Plots contain 10th and 90th percentiles of forecast residuals from WY 1956 to 2005, provided as a percentage of mean annual flow (parentheses). Skill of VIC-based forecasts (color) is comparable to or better than that of ground-based forecasts (black). Efforts are underway to increase VIC resolution to 1/16° for all 14 watersheds and expand forecasts to earlier in the water year.

Task 6: Retrospective assessment (Klamath and Sacramento)

"We will undertake a retrospective assessment of forecast system performance in both study areas to serve as the basis for evaluation and modification of the forecast system. To the extent possible given the limited period of record of remote sensing data sources such as MODIS, we will perform retrospective forecasts made in a manner consistent with real-time operation, and evaluate changes in forecast skill due to incorporation of remote sensing data, and ensemble climate forecasts. We will present results of the retrospective evaluation at one or more of the planned one-day workshops (Task 5)."

Several retrospective assessments were conducted for Task 6. At the outset of the study, hindcasts of April–July runoff were performed for the Feather R basin to establish baseline forecast skill levels. Retrospective forecasts were initiated on the first of the month from January to June to replicate procedures used operationally. The hindcasts showed adequate correlation with observations, but the uncertainty bounds provided by the ESP forecast technique (which is a baseline approach used operationally in the NWS) were erroneously narrow, suggesting forecast overconfidence. As a result, we explored a forecast calibration approach that corrects for uncertainty errors, based on using the ESP mean as a single value forecast and formulating the uncertainty from both forecast correlation and climatological information. The resulting forecast error distributions match those observed during the 56 year hindcast period (Figure 5). This technique was later implemented as a central part of the project's forecasting system.

As part of the ET estimation system developed in Task 2, the VIC model was employed in the Upper Klamath River basin to estimate ET from 1950 to 2005, with the VIC lake module used to estimate ET in grid cells containing marsh, wetlands, and lakes. The long-term mean inflow to Upper Klamath Lake of the calibrated model was found to have a 1% bias when compared with estimates from the U.S. Bureau of Reclamation. A retrospective simulation of Upper Klamath Lake was performed from 1950 to 2005 based on the 1/16 degree VIC model and a one-year estimation of irrigation water requirements. Simulated daily water storage and water level values agreed well with USGS observations. Comparisons of irrigation water amounts estimated by the satellite-based system with those derived from irrigation canal observations from 2001 to 2005 yielded favorable agreement.

Publications resulting from this task:

Wood AW, Schaake JC (2008) Correcting errors in streamflow forecast ensemble mean and spread. J of Hydrometeorology, 9:132-148

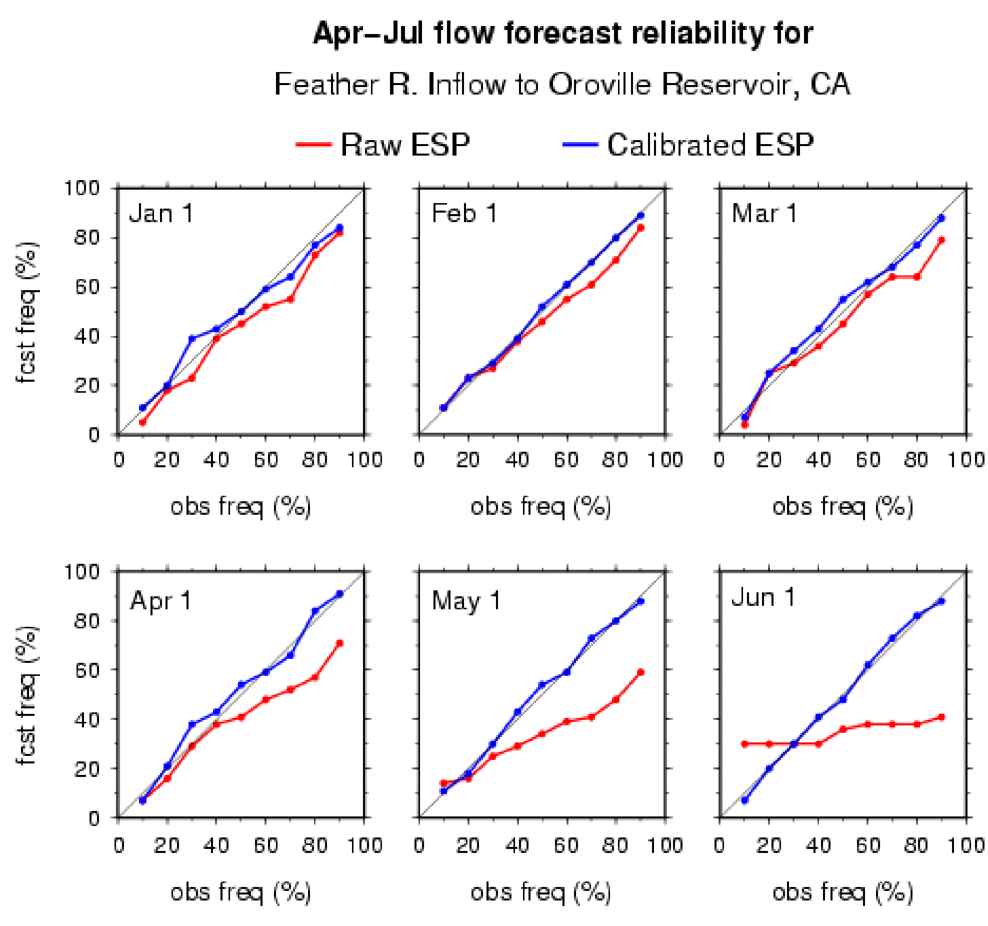

Figure 5: Reliability diagrams for the raw and calibrated hindcast ensemble distributions for the Feather R. basin. The raw ESP ensembles (red) show increasing overconfidence and under-simulated dispersion, as well as bias, as the forecast season progresses. The calibration approach restores the uncertainty to the forecast ensembles, so that the observed and forecast frequencies (blue) fall close to a 1:1 line on the reliability diagram.

Task 7: Transition to operations

"In Year 3, before the final forecasting season, UW/UCI research team members will meet with NWCC, USCR, and DWR operational staff to plan permanent migration of those forecast elements that have performed the best into operations. As the final forecast season progresses, the UW/UCI team members will train operational staff and prepare documentation manuals that will enable NWCC and DWR to operate the forecast system independently. Team members will make frequent trips to Portland and Sacramento during that period to troubleshoot and address any complications stemming from migrating the forecast system from the research center to the operational center, until the conclusion of the project."

Much of this effort involves the studies described in Task 5, which are designed to integrate hydrologic models and remote-sensing data within the operational framework of DWR's Division of Flood Management (David Rizzardo, Chief of Snow Surveys and Water Supply Forecasting, has been our primary contact in that regard). Several users have also expressed interest in the ET estimation product, including USBR's Yakima Project and the Modeling Support Branch at DWR. In addition, a number of researchers have requested the ET product for operational water management studies, including the University of Illinois at Urbana-Champaign and the University of Texas, Austin.

References:

Zhao H, Fernandes R (2009) Daily snow cover estimation from Advanced Very High Resolution Radiometer Polar Pathfinder data over Northern Hemisphere land surfaces during 1982–2004. J Geophys Res 114(D05113):1–14